Infrared materials and devices of III-V arsenides and antimonides by molecular beam epitaxy

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Abstract:

Infrared electroabsorption modulation in AlSb/InAs/AlGaSb/GaSb/AlSb stepped quantum wells grown by molecular beam epitaxy was achieved. Molecular beam epitaxial growth of GaInSbBi for 8-12 um infrared detector applications was demonstrated for the first time. AlAsSb/InAsSb heterojunction diodes were achieved on Si substrates by molecular-beam epitaxy with a suitable breakdown voltage for device applications. Narrow band gap InAs high electron mobility transistors with heterojunction AlSbAs barriers were demonstrated. AlGaAs/GaAs Npn heterojunction bipolar transistors grown on Si (311) by molecular beam epitaxy with a record emitter-collector breakdown voltage of 13 V were achieved.

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During the grant period (Nov. 1, 1994 to Oct. 31, 1997), the following research results were achieved:

Infrared electroabsorption modulation in AlSb/InAs/AlGaSb/GaSb/AlSb stepped quantum wells grown by molecular beam epitaxy

The first experimental results of normal-incidence infrared electroabsorption modulation based on an asymmetric AlSb/InAs/$Al_{0.4}Ga_{0.6}$ Sb/GaSb/AlSb double QW structure grown on a (100) *p*-type GaSb substrate were reported. The modulation of the absorption coefficient Δ_α was obtained to be as large as 3200 cm^{-1} under 14 V reverse bias at 77 K, which is the largest ever observed.

As an electric field is applied to the structure, the first G subband moves up while the first *L* subband moves down because these two step wells are oppositely biased. As a result, the electrons transfer from $\Gamma_{1\Gamma}$ states to L_{1L} states through interwell tunneling and therefore the normal-incidence modulations can be achieved efficiently under a moderate bias.

The GaSb well layer thickness was adjusted to 30 Å to obtain the expected modulation wavelength range ~3–5 μm, while the thickness of the InAs layer was 12 Å. The thick-ness of the InAs layer was chosen because it is thin enough to push the first Γ subband up close to the first *L* subband in the GaSb well, thus avoiding a large bias for the Γ-*L* tran-sition. The device breakdown voltage is also increased due to the increase of the InAs effective energy gap. Between the InAs and the GaSb wells, a 100 Å $Al_{0.4}Ga_{0.6}$ Sb space layer was inserted to increase the modulation efficiency. The tradeoff between modulation efficiency and modulation volt-age was considered in designing the optimized spacer thickness because it is directly proportional to the modulation efficiency and voltage, respectively.

It is found that the modulation absorptions strongly depend on the biases. When the applied bias is decreased, Δ_α decreases due to less electron carriers occupying the *L* states since the normal incidence absorption is only allowed for the L_{1L} -L_{2L} transition. A magnitude of modulation Δ_α as high as 3200 cm^{-1} was obtained at 14 V reverse bias, using the absorption coefficient as a reference at zero bias. The peak wavelength undergoes a blueshift with increasing of the applied biases, as expected. At zero bias, the absorption peak wavelength is at 6.5 μm, while in the presence of a 14 V reverse bias the peak wavelength shifts to the expected wavelength of 5 μm.

Molecular beam epitaxial growth of GaInSbBi for infrared detector applications

Given the covalent atomic radii of In, Sb and Bi (1.44, 1.40, and 1.46 Å, respectively), it is clear that the lattice constant of the epilayer is increased with increased Bi content, thus increasing the lattice mismatch to the InSb substrates. As a result, Bi, the largest atom, is squeezed out of its lattice site in the lattice-mismatched layer; therefore,inducing the formation of a second phase and limiting the Bi content.

In this work, the growth and optical properties of $Ga_{0.04}In_{0.97}Bi_{0.03}$ films grown by MBE on InP substrates is reported and it is demonstrated that increased Bi content in high-quality crystals can be achieved by the incorporation of Ga into the InSbBi alloy, In addition, (3 1 1)A and (5 1 1)A oriented growth is shown to increase the incorporation of Bi and improve surface morphology further.

Ga was incorporated into the InSbBi alloy in order to reduce the lattice constant and improve the lattice match to InSb (the covalent atomic radius of Ga is 1.26 A. which is much smaller than that of Sb and Bi). Although the introduction of Ga to InSb increases the band gap, the increase is minimal for a low Ga content due to the band gap narrowing near the InSb end of the ternary alloy (the band gap for $Ga_xIn_{1-x}Sb$ is given as $0.172 + 0.139x + 0.415x^2$ at 300 K). In addition, film composition can be easily controlled by MBE as GaInSb is a group III alloy with only one group V element. This technique of "lattice compensation" is widely applicable and may also be applied to other narrow gap compounds, such as adding Ga to InTlSb and InAsN.

The dependence of surface morphology on substrate orientation is best understood when one considers the surface bonding structure of various substrate orientations. The atoms on the (1 0 0) surface each has one double-dangling bond, while each (111)A surface atom has one single dangling bond. The (5 1 1)A surface (16 degree off (1 0 0) toward (1 1 1)A) is composed of both single- and double-dangling bond sites as the flat (100) terrace consists of two terrace atoms, each with double-dangling bonds, and one step edge atom with one single-dangling bond. For (*n* 1 1)A-oriented substrates, the step-edge group III atom has a very stable configuration, providing a favorable bond-site for Sb and Bi.

The large angle off-axis substrates (i.e., (3 1 1)A and (5 1 1)A) were critical for the incorporation of Bi in the films and for sustaining two-dimensional crystal growth. Although Bi content did not increase significantly for the (3 1 1)A and (5 1 1)A-oriented films as compared to the (1 0 0)-oriented films, the surface morphology for (3 1 1)A and (5 1 1)A is significantly superior, most likely due to the absence of multiple phases. Most importantly, all GaInSbBi films grown on the (1 0 0)-orientation did not show an extension of the cutoff wavelength. Only films grown on (3 1 1)A and (5 1 1)A exhibited a band edge that was clearly extended to longer wavelengths.

The dependence of the surface morphology and optical absorption of GaInSbBi films on growth temperature was investigated for the substrate temperature range 300 and 380 °C. Within this range of substrate temperature investigated, a higher growth temperature was found to result in a superior surface morphology, which was also evidenced from the streaky RHEED patterns during crystal growth indicating a two-dimensional nucleation. Lower substrate temperatures often resulted in more spotty RHEED patterns possibly due to the lower surface mobility of adatoms at lower temperatures. However, optical absorption measurements using Fourier transform infrared spectroscopy (FTIR) indicated that the GaInSbBi films grown at lower substrate temperatures exhibited an absorption edge at longer wavelengths (corresponding to an increased Bi content). This indicated that the sticking coefficient of Bi is higher at lower substrate temperatures, which is consistent with previous reported results.

The Sb flux was varied during the growth of the GaInSbBi films in order to investigate the nucleation competition between Sb and Bi. Our results indicated that an Sb-rich condition resulted in a nearly-zero Bi sticking coefficient, while an Sb deficient condition (i.e. Sb/(Ga + In) ratio slightly less than unity) enhanced the Bi incorporation. Again, this is consistent with previously reported results.

The FTIR spectrum at 77 K indicated an extended absorption wavelength, 10.7 μm, for $Ga_{0.04}In_{0.96}Sb_{1-x}Bi_x$, films grown under Sb-deficient conditions. In addition, two absorption regions were observed, corresponding to the InSb and $Ga_{0.04}In_{0.96}Sb_{1-x}Bi_x$, films. Based on a 36 meV decrease in energy gap per atomic percentage of Bi increase, Bi content was estimated to be roughly 3%.

AlAsSb/InAsSb heterojunction diodes grown on Si by molecular-beam epitaxy

$InAs_{1-x}Sb_x$ grown on GaAs and Si has attracted much attention recently due to its potential for application in monolithic infrared detectors integrated with electronic read-out circuits. InAsSb diodes grown on slightly lattice-mismatched InSb, GaSb, and InAs substrates have been reported, but the problem with this approach is that it is difficult to fabricate signal processing circuits on these substrates. Therefore, the growth of InAsSb on highly lattice-mismatched GaAs and Si substrate becomes attractive and InAsSb homojunction photodiodes on GaAs and Si sub-strates have been demonstrated. However, the large lattice-mismatch between InAsSb and the GaAs or Si substrates inevitably results in a high density of vertical threading dis-locations which originate from the substrate–epilayer interface and extend into the epilayer. In order to accommodate the large lattice mismatch and improve epilayer quality, several different buffer layers were employed and studied.

In this work, the successful growth of InAsSb on Si substrates using an AlSb intermediate buffer layer and an InSb/GaSb strained-layer superlattice which effectively reduces threading dislocation density extending into the InAsSb epilayer is reported.

A new lattice-matched $AlAs_{0.08}Sb_{0.92}/InAs_{0.91}Sb_{0.09}$ heterojunction diode grown highly lattice-mismatched to an Si substrate is also reported. This heterojunction diode has several advantages. Because $AlAs_{0.08}Sb_{0.92}$ cap layer is transparent to infrared radiation, infrared photons are absorbed in the active n-type InAsSb layer only and are collected by both drift and diffusion mechanisms; and a zero valence band offset ~DEv 10 of the heterojunction facilitates the collection of holes and reduces the probability of electron–hole recombination in the depletion region.

The $AlAs_{0.08}Sb_{0.92}/InAs_{0.91}Sb_{0.09}$ heterojunction structures consisted of a 2 um $1*10^{18}$ cm^{-3} Si doped n-type InAsSb layer, a 1.5 um undoped InAsSb active layer, a 2000 Å $2*10^{18}$ cm^{-3} Be doped p-type AlAsSb layer and a 200 Å $2*10^{18}$ cm^{-3} Be doped InAs cap layer to prevent AlAsSb from oxidation. Although there is a slight lattice-mismatch between InAs and $AlAs_{0.08}Sb_{0.92}$, the 200 Å InAs cap layer is below the critical thickness for dislocation generation. It is important to have AlAsSb lattice matched to InAsSb in order to obtain a good heterointerface which will reduce interface leakage current in the heterojunction diodes. The composition of $AlAs_ySb_{1-y}$ and $InAs_{1-x}Sb_x$ epilayers was determined by four crystal x-ray diffraction measurements. Lower background doping of the InAsSb active layer would reduce tunneling leakage current. Therefore, Hall effect measure-ments were performed to determine the background doping of the undoped $InAs_{0.91}Sb_{0.09}$. Carrier concentrations of $n=1*10^{17}$ cm^{-3} and $n=5*10^{16}$ cm^{-3}, and electron mobilities of $u=1.4*10^4$ cm^2/V s and $u=1.3*10^4$ cm^2/V s at 300 and 77 K, respectively, were obtained for a 3 mm thick $InAs_{0.91}Sb_{0.09}$ layer grown on (100) Si using the buffer layers mentioned above. The decrease in mobility with decreasing temperature is caused by dislocation scattering and ionized impurity scattering, which control the transport properties at low temperature.

For a typical $I - V$ characteristic of an $AlAs_{0.08}Sb_{0.92}/InAs_{0.91}Sb_{0.09}$ $p+n$ heterojunction diode without passivation at 300 K. The reverse leakage current is strongly voltage dependent at reverse bias greater than 1 V, indicating that band-to-band tunneling dominates. For small reverse bias, the leakage current is controlled by the thermal transport mechanism.

AlAsSb/InAsSb heterostructure *p-n* junction diodes have been successfully grown on Si substrates by MBE with the employment of a strained superlattice buffer layer. Based on their good current–voltage characteristics at room temperature, these heterojunction diodes are promising for 3–5 um infrared detector applications.

Narrow band gap InAs high electron mobility transistors

Enhancement-mode InAs n-channel high electron mobility transistors (E-HEMTs) are realized by incorporating a beryllium (Be) doping sheet within the upper barrier and utilization of an InAs surface layer. At room temperature, n-channel E-HEMTs with 1 μm gate length exhibit extremely low output conductance (12 mS mm^{-1}), high extrinsic transconductance (425 mS mm^{-1} for $V_{DS}=0.8$ V), and near zero threshold voltage. Our results demonstrate enhancement-mode operation of an InAs/AlSb heterojunction field-effect transistor.

AlSb/InAs n-channel inverted-structure high electron mobility transistors (i-HEMT's) are realized by incorporating a Si doping sheet into a thin InAs layer that is embedded within the lower AlSb barrier. i-HEMT's with a 1μm and 25 μm gate size exhibit kink-free operation at room temperature with high drain current, high extrinsic transconductance, and low gate leakage. Results indicate potential for use in high-speed applications.

Transmission line measurements performed on AlSb/GaSb heterostructure buried InAs n-channels incorporating AuGe- and AuTe-based ohmic contacts show that the optimum contact resistance for Ni/AuGe/Ni/Au metallization is achieved at 325 degrees C for a 20 s annealing process ($rho_c=2.3*10^{-7}$ Omega cm^2, a record low for an

AlSb/GaSb structure), whereas only $1.3*10^{-6}$ Omega -cm^2 is obtained for the Ni/AuTe/Ni/Au system optimally annealed at 400 degrees C. Uniform alloyed surface morphology is observed in Ni/AuGe/Ni/Au contacts, while the blistered surface appearance of the Ni/AuTe/Ni/Au system correlates with degraded performance. Measured dc and microwave characteristics of 1μm gate length InAs n-channel high electron mobility transistors using AuGe- and AuTe-based source/drain contacts show that ohmic contact quality is critical to device performance.

AlGaAs/GaAs Npn heterojunction bipolar transistors grown on Si (311) by molecular beam epitaxy

There has been much interest in the heteroepitaxy of GaAs-on-Si due to the potential for integration of high performance GaAs-based optoelectronic devices with Si large scale integration technology. The high-power operation and superior cut-off frequency of AlGaAs/GaAs heterojunction bipolar transistors (HBTs) and enhanced heat dissipation via Si substrates render the integration of HBTs-on-Si an especially attractive prospect for high-power applications. However, carrier lifetime reduction due to the formation of anti-phase domains (APDs), lack of electrical neutrality at the epilayer/substrate interface, and high dislocation densities associated with polar-on-nonpolar GaAs-on-Si growth, remains as the dominant limiting factor to HBT-on-Si performance.

The growth of AlGaAs/GaAs HBTs on Si (311) substrates by molecular beam epitaxy has been reported. The reduced step height and zinc-blende compatible sublattice nucleation renders the (311) orientation a viable candidate for the achievement of high-quality APD-free epilayers with smooth morphology and low stacking fault densities.

The common-emitter $I-V$ characteristics of the AlGaAs/GaAs HBT with an emitter area of 70*70 um^2, exhibit a maximum dc current gain of 6 at a collector current density of 3.1 kA/cm 2 , a small-signal common-emitter current gain of 10 at a dc collector current density as low as 1.8 kA/cm^2 and a collector-emitter breakdown voltage of BV_{CEO}=13 V. The collector offset voltage, V_{CE} at I_C=50, is measured as 300 mV while the ideality factors of the base-emitter and base-collector junctions are deduced from I_B and I_C dependence on V_{BE} ,(V_{BC}=50) as 2.2 and 1.4, respectively. The relatively high ideality factor of the emitter-base junction can be attributed to a high space-charge recombination rate (possibly within the undoped set-back $Al_{0.05}Ga_{0.95}As$ region which was used in order to prevent Be diffusion into the AlGaAs emitter). These results indicate that further optimization in growth technique may render the growth of GaAs-on-Si (311) a viable candidate for application in high-power integration.

AlGaAs/GaAs *Npn* HBTs-on-Si (311) grown by MBE are reported. *In situ* monitoring of RHEED patterns correlate with APD-free growth. A 70*70 mm^2 HBT grown on a GaAs buffer layer as thin as 2 mm exhibits a small signal common-emitter gain of 10 at a dc collector current density of 1.8 kA/cm^2 and a collector-emitter breakdown voltage as high as BV_{CEO} =13 V.

Publication List

1. Du Q, Alperin J, Wang WI. "Normal incidence infrared modulators using intersubband transitions in InAs/GaSb/AlSb stepped quantum wells grown by molecular beam epitaxy". ***Journal of Vacuum Science & Technology B***, vol.14, no.3, May-June 1996, pp.2343-5.

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